RESEARCH AND DEVELOPMENT

PHASE II: RESEARCH AND DEVELOPMENT OF ENGINEERING PROTOTYPE

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I. COIL DESIGN

The coils used for the transmitter, receiver and transponder must be designed to give the largest system sensitivity. At the same time, the coil size must be kept within practical limits. An analysis of the effect of coil parameters on the system sensitivity[1] showed that the Q of the transmitter and transponder coil should be a maximum. The Q of the receiver coil should be maximum for the case where the receiver input is tuned. For the case where the receiver input is untuned, the quantity nQ must be made a maximum where n is the number of turns.

The Q of a coil is largely influenced by the ac resistance and the distributed capacity of the coil where for a given inductance largest Q occurs when Rac and Cd is a minimum.

The distributed capacity is largely determined by the type of coil winding used and to a lesser extent by the wire size and insulation used. We have found that spider-web type winding gives the least distributed capacity.

The ac resistance of the coil is a measure of all the losses that occur in the coil. The losses can be minimized by the use of the proper kind of wire, namely Litz wire.

An investigation was made on the effect of wire size on coils wound in spider-web fashion on masonite coil forms. These forms were of the type shown in Appendix A but with 17 pegs, an outside

[1] See report on Phase I, pp 26 et seq.

diameter of 15" and inside diameter of 8.5". Six different coils were wound with the following number of turns and wire sizes:

Coil #1	75 turns of #18 wire
Coil #2	75 turns of 52 strands of #38 wire
Coil #3	75 turns of #24 wire
Coil #4	75 turns of 10 strands of #41 wire
Coil #5	133 turns of 52 strands of #38 wire
Coil #6	200 turns of 10 strands of #41 wire.

The Q meter was not available for the measurements of the coil parameters; therefore, the circuit shown in Figure 1 was used. The output of a signal generator was applied to a 1000 ohm resistor and adjusted to maintain 0.01 volt reading on the first voltmeter. The capacitor was adjusted for maximum voltage reading of the second voltmeter. A "phantom repeater" was used to isolate the voltmeter and prevent loading of the circuit. It has an input impedance of about 200 megohms shunted by a six to eight micromicrofarad capacity in the frequency range of 50 to 150 KC. When the coil under test and C are in resonance at the frequency of the applied voltage, the voltage across C is Q times the voltage across the 1000 ohm resistor. Thus, Q is given by the ratio of the voltage across C to the voltage across the resistor.

The distributed capacity was determined by measuring the self resonant frequency of the coils and the resonant frequency of

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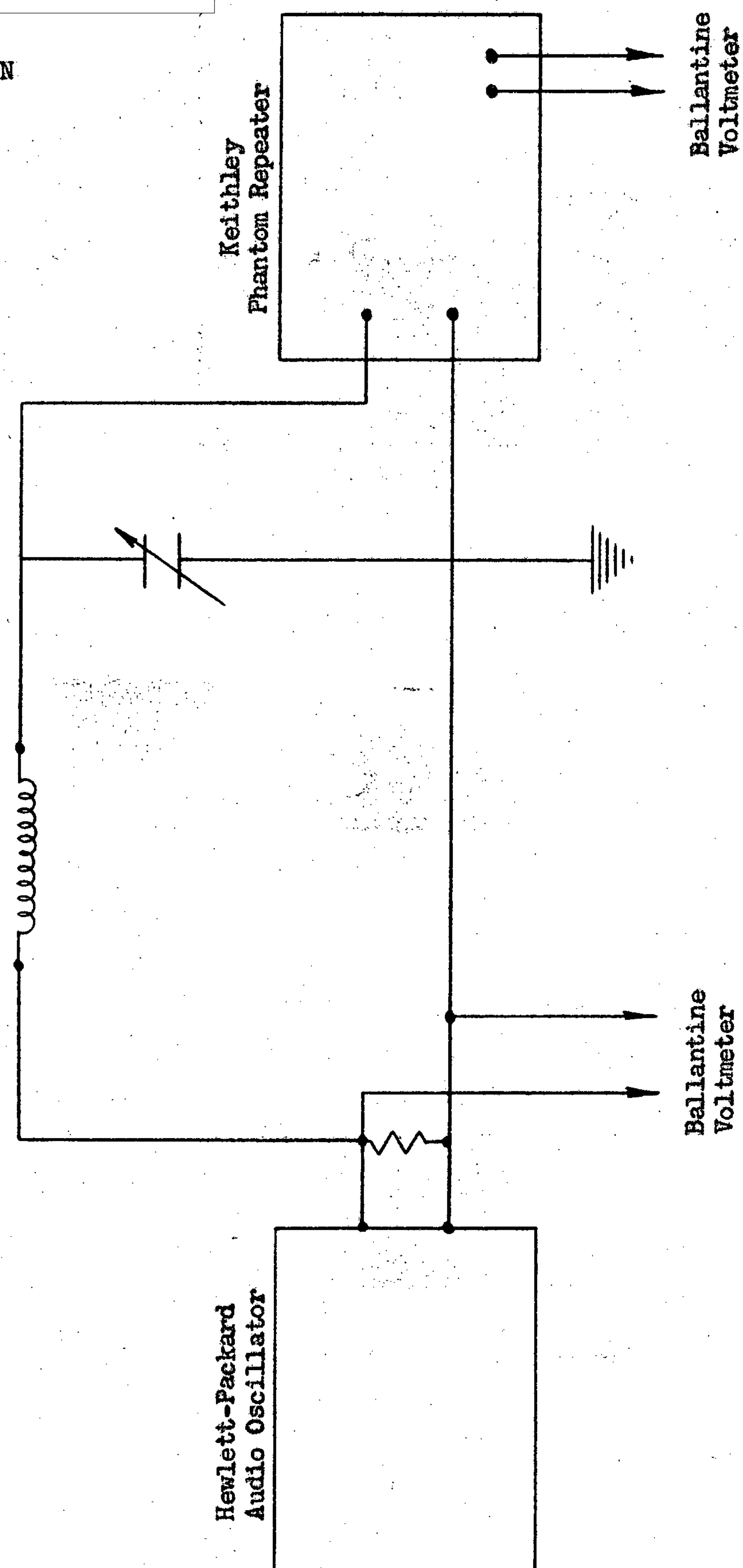

Figure 1. Circuit for Measuring Coil Parameters

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when a known amount of capacity was added. C_d is then given by:

$$C_d = \frac{C_1}{\left(\frac{f_o}{f_1}\right)^2 - 1}$$

where f_o = self resonant frequency of the coil, C_1 = capacity added to the coil to give f_1 as the resonant frequency. After C_d is evaluated the inductance L of the coil is given by:

$$L = \frac{1}{W_1^2(C_d + C_1)}$$

The results of these measurements are presented in Table I.

TABLE I

Coil	Wire Size	Turns	C_d	L	Max. Q	f max Q
#1	18	75	14.57 μμf	1.93 mh	150	115 KC
#2	52/38	75	14 μμf	2.38 mh	230	105 KC
#3	24	75	11.5 μμf	2.07 mh	112	107 KC
#4	10/41	75	10.7 μμf	2.46 mh	56	115 KC
#5	52/38	133	18.4 μμf	4.52 mh	191	82 KC
#6	10/41	200	16.5 μμf	17.2 mh	76	67 KC

We can see that the distributed capacity decreases as the wire diameter decreases. Coil #2 wound with 52/38 has the highest Q. This Litz wire is made with the strands insulated from each other and laid together without any braiding. Braiding should reduce the ac resistance. We are at present trying to procure braided Litz wire. Belden Manufacturing Company at Chicago has agreed to supply us with nine different types of braided Litz wire in 1000 foot lengths.

II. SYSTEM DESIGN

During this initial period of Phase II, work was performed on all three of the proposed systems - the crossed-coil system, the pulsed system, and the balanced-coil system. In addition, some simple experiments were performed on a grid-dip system.

A. Crossed Coil System

The basic difficulty with this system at the state of its development at the end of Phase I was the signal present in the receiver coil without the transponder being present. The sources of this signal are the transmitter coil and external noise generators such as flourescent lights, etc. The signals due to the transmitter coil are caused by both magnetic and capacitive coupling. This residual voltage in the receiver places a limit on the smallest signal that can be detected and thus is significant in determining the maximum range at which the transponder can be detected.

There are two apparent approaches to the solution of this problem. One method is to balance out the residual voltage in the receiver by introducing a voltage from the transmitter into a subtracting circuit arranged to cancel the residual voltage due to pick up from the transmitter coil. The voltage from the transmitter must be fed through a phase-shifter and attenuator to match the residual voltage. In doing this, we encountered difficulties due to the variation of phase-shift with frequency and the mechanical instability of the coil mounting.

The second approach is to eliminate the trouble at the source. This requires a more stable mechanical system, proper shielding, and a means for adjusting the orientation of the receiver coil with respect to the transmitter coil without interfering with the field distribution. This second approach is now being pursued.

B. Pulsed System

The pulsed system uses a transmitter which is pulse-modulated and a receiver which amplifies the induced "ringing" signal from the transponder. In addition to the "ringing" signal from the transponder, the receiver coil picks up the pulses from the transmitter, which are much greater than the transponder signal. The circuit that was used in Phase I of this project gave a low signal to noise ratio. In order to be able to use smaller coils the signal to noise ratio in the receiver must be

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greatly improved. This period has been spent in examining different clipper amplier circuits and gate circuits. There is nothing conclusive to report at this time.

C. Balanced Coil System

The balanced coil system uses a transmitter consisting of an oscillator driving two amplifiers with parallel input and push-pull output. The output circuits consist of two tuned circuits which are connected so as to have the voltages opposing each other. One tuned circuit radiates while the other circuit does not; the latter utilizing a toroidal coil and adequate shielding. The receiver input is the difference between these two voltages which is adjusted for a minimum when not in the presence of the transponder.

This system was described in the Phase I report as one which would be brought to the bread-board stage in order to compare it with the other systems. This work has been started. The toroidal coil must match the radiating coil to such a degree as to give a voltage difference of the order of one millivolt. Thus far, we have been unable to match coils to a sufficient likeness to achieve this.

D. Grid-Dip Oscillator

The grid-dip oscillator is a system which was not attempted in Phase I but was considered in the early part of this period. A simple experiment was performed using a Hartley oscillator with a DC amplifier to amplify the variations of grid voltage due to the transpondor. The transpondor produced an observable change in the output of the DC amplifier at distances up to ten feet. These results indicated that this system, with modifications, might prove to be a satisfactory solution to the problem. It should be considered along with the other systems.

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INTRODUCTION

The purpose of the field tests was to determine experimentally the attenuation of electromagnetic waves in soil. Theory indicates that the attenuation should be small for the frequency range of 50 to 150 kc. The results of the experiment are in general agreement with the calculations.

Description of Experiment

The site consisted of two ditches 2 feet wide, 6 feet deep and 25 feet long. The trenches were parallel to each other and were separated by a wall 5 feet wide. The soil was a mixture of gravel, clay, and sand.

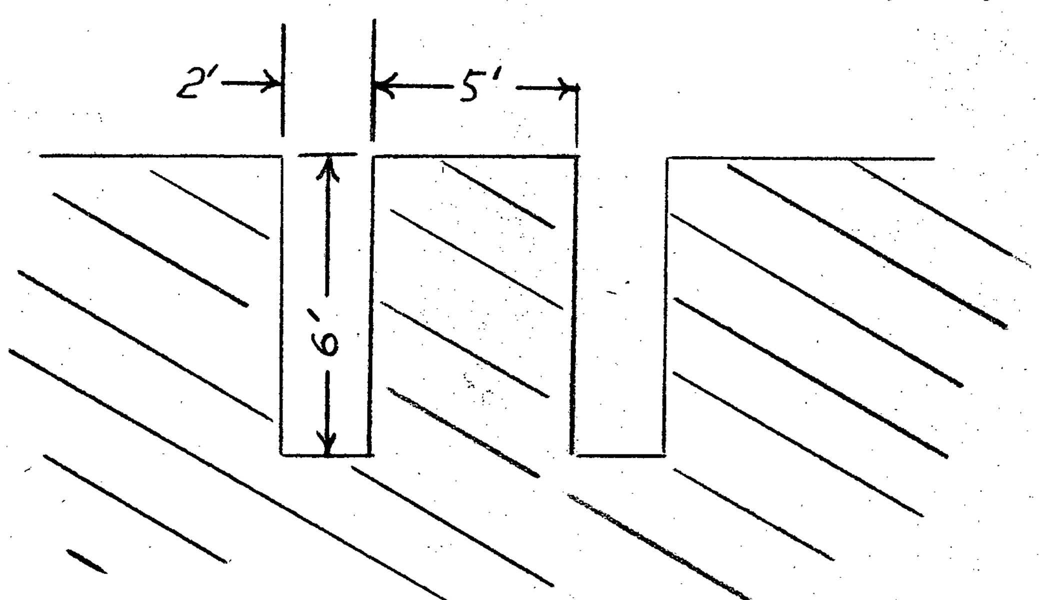

Figure 1. Cross Section of Test Site

The equipment used for the experiment consisted of two identical coils[1], one used as the transmitter and the other as the receiver.

1 See APPENDIX A for Coil Parameters.

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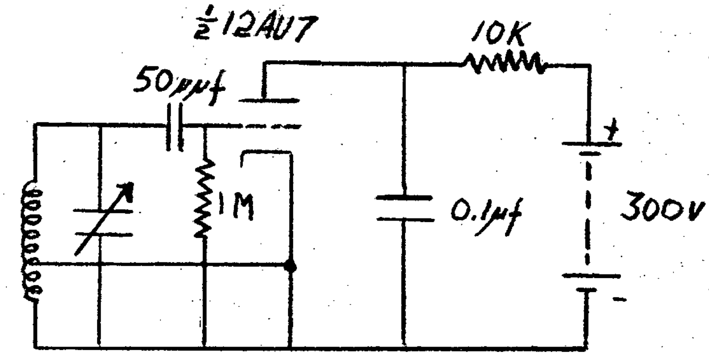

Figure 2. Transmitter Circuit

The transmitter circuit, shown in Figure 2 consisted of a Hartley oscillator operating at 90.4 kc. Plate and filament voltages were supplied by means of batteries.

The receiver, shown in Figure 3 consisted of a tuned circuit and a battery-operated Ballantine voltmeter.

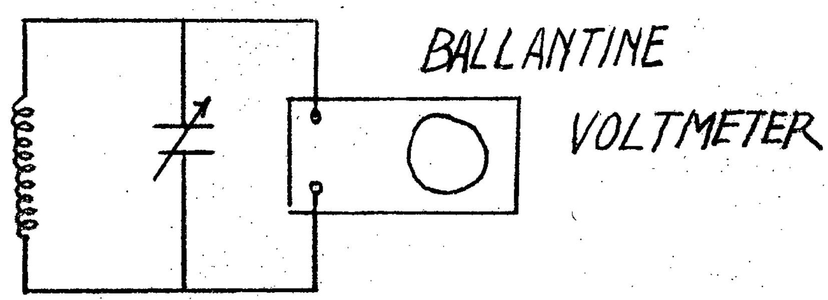

Figure 3. Receiver Circuit.

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Wooden frames supported the transmitter and receiver in position. The transmitter was placed in one trench and the receiver was placed in the other trench so that transmission of the signal from transmitter to receiver was through the 5-foot wall of earth. The plane of each coil was maintained parallel to the trench walls.

Initially, the coils were placed opposite each other. The receiver was kept stationary and the transmitter was than moved in steps of 3 feet along the length of its trench. The voltages induced in the receiver at each of these intervals were recorded. This configuration is essentially equivalent to the transpondor's being buried 5 feet down, with the transmitter coil held above and parallel to the ground.

The induced voltage in the receiver was also measured under conditions where the transmission was through air and the distance separating the two coils was the same as their minimum separation in the trenches.

A reading was taken of the receiver output with the transmitter turned off, to make sure that the voltages measured were not due to unknown sources. This reading over a five minute period was less than 1 millivolt, which is the lowest voltage the Ballantine voltmeter will indicate.

<u>Experimental Data</u>

The measured rms voltages are labeled according to the positions shown in Figure 4.

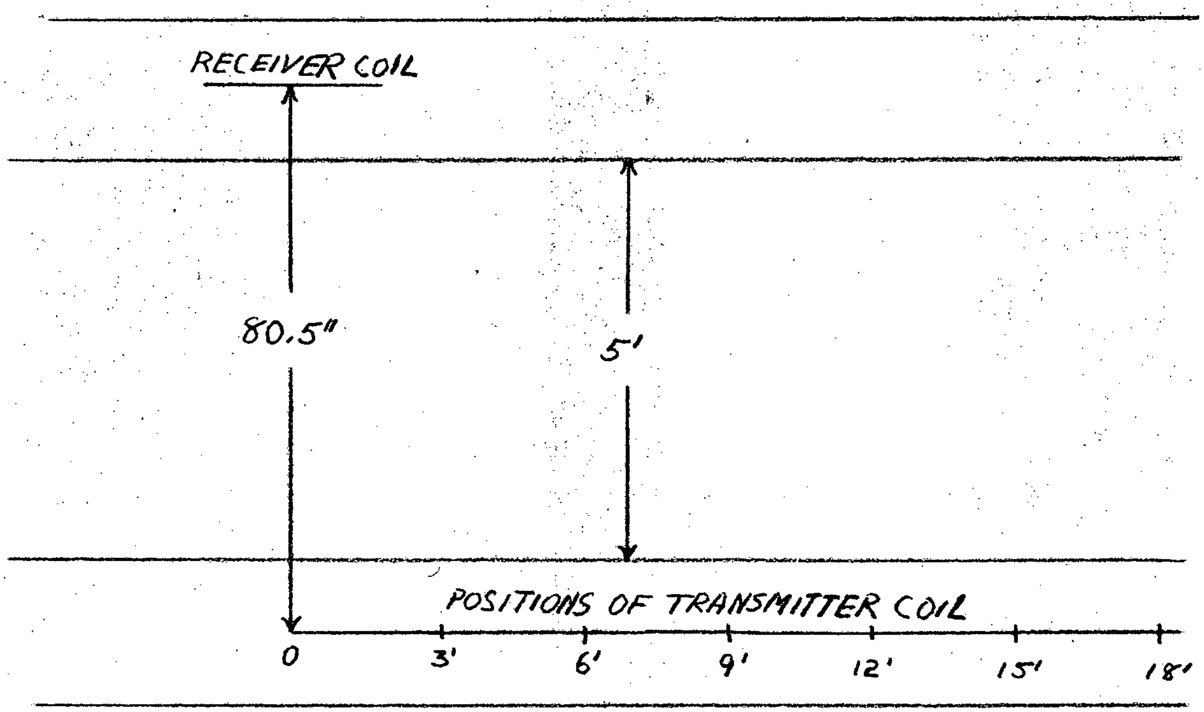

Figure 4. Positions of Transmitter with Respect to Receiver

The results of four runs are shown in Table 1.

Table 1

	Run 1	Run 2	Run 3	Run 4
0'	28 V	23 V	21.0 V	22 V
3'	16 V	14 V	7.0 V	12.0 V
6'	1.6 V	1.8 V	1.7 V	2.0
9'	0.03V	0.15V	0.13	0.06V
12'	0.27V	0.21V	0.18	0.22V
15'	0.22V	0.20V	0.21	0.21V
18'	0.15V	0.15V	—	0.12V

The induced voltage in the receiver measured for transmission through air with a separation of 80.5" between transmitter and receiver coil was 24.0V.

Several measurements were made where the transmitter coil was rotated for maximum signal at the receiver. It was found that, except for the 0' position, a signal maximum was measured at the receiver for two particular positions of the transmitter. These positions were found by rotating counterclock wise and clockwise with respect to the position of being parallel to the trenches.

<u>Comparison of Experimental Data with Theory.</u>

The induced voltage in one coil due to a second energized coil, for the case where the two coils are maintained parallel, was calculated in the Phase I report. The ratio of the induced voltage at some position θ (see Figure 5) to the position of minimum distance ($\theta \simeq 0$) is given by

$$\cos^3 \theta \left(\tfrac{3}{2}\cos^2\theta - \tfrac{1}{2}\right)$$

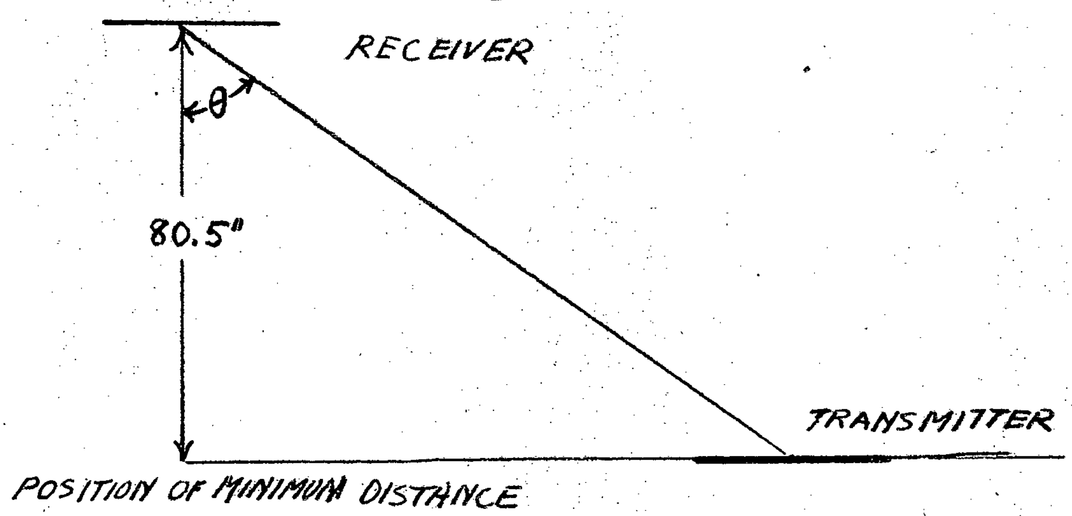

Figure 5. Configuration of Transmitter and Receiver

where the transmission path is in air. This expression has been verified experimentally for transmission in air. Thus, since no attenuation factor was considered in the derivation, we can conclude that attenuation in air can be neglected.

In order to compare experimental results with theory, the expression given above was evaluated for values of θ corresponding to the 3', 6', 9' etc. positions. These results are given in Table II.

Table II

Position	θ	$\cos^3\theta\,(\frac{3}{2}\cos^2\theta-\frac{1}{2})$
0'	0	1
3'	25.5	0.532
6'	41.8	0.137
9'	53.3	0.00725
12'	60.8	0.0166
15'	65.9	0.017
18'	69.5	0.013

The experimental data was reduced to the same form by dividing the voltages measured at the receiver for the different positions by the voltage at the receiver for the 0' position. In addition, to facilitate comparison these ratios were divided by the corresponding values of the theoretically expected value given in Table II. Table III gives the result of these computations. We have labelled the voltage ratio η i.e. voltage at 0', 3', 6', etc. to voltage at 0' position. The expected value for this ratio as given by the expression of Table II has been called E.

Table III

Position	Run 1	Run 2	Run 3	Run 4	ave η	$\frac{\text{ave } \eta}{E}$
3'	0.572	0.608	0.333	0.546	0.512	.962
6'	0.057	0.0783	0.0808	0.110	0.0815	0.595
9'	0.0017	0.00652	0.00618	0.00273	0.00428	0.592
12'	0.00964	0.00913	0.00857	0.010	.00934	0.562
15'	0.00786	0.00870	0.010	0.00955	0.00903	0.531
18'	0.00536	0.00652	——	0.00546	0.00578	0.445

The values for ave η/E indicate that attenuation exists, since their magnitude decreases with increase in distance.

If we assume the attenuation is of the form e^{-kr} where k is the absorption coefficient and r is the distance travelled through the absorbing medium, then the theoretically expected value should be of the form

$$\cos^3\theta\,\left(\tfrac{3}{2}\cos^2\theta-\tfrac{1}{2}\right)\frac{e^{-kr}}{e^{-kr_o}}\,.$$

The factor e^{-kr_o} appearing in the denominator is the attenuation factor for transmissio directly through the 5' wall. It is introduced to take care of the fact that we have divided by the voltage reading at the receiver for the 0' position.

The values for ave η/E thus have the expected value as given by

$$e^{-k\,(r-r_o)}$$

and is equal to unity when $r = r_o$ where $r_o = 5'$ which is the width of the wall separating the two trenches. By taking the log of both sides of the equation:

$$\frac{\text{ave}\ \eta}{E} = e^{-k(r-r_o)}$$

we get

$$\ln\left(\frac{\text{ave}\ \eta}{E}\right) = k(r-r_o).$$

Using the method of least squares we can evaluate k by

$$\sum_i \ln\left(\frac{\text{ave}\ \eta_i}{E_i}\right) = k\sum_i (r_i-r_o)$$

where the summation is over the experimental values for the various positions. The distance travelled through the absorbing medium is given by $\frac{5'}{\cos\theta}$. The value for k evaluated by this method is 0.113. The value of $r - r_o$ for the field to fall off to 1/e is 8.85 or r = 13.9 feet. The mean deviation for k is ± 0.086. This gives 0.027 and 0.199 for the probable limits of k which correspond to r equal to 42 feet and 10.02 feet. A value for k was also obtained from the average value of receiver voltage with transmitter in the 0' position and the voltage obtained with the same separation of transmitter and receiver in air. For these data k = 0.004 and r = 250 feet for an attenuation of $\frac{1}{e}$.

The distance for the field to fall off to $\frac{1}{e}$ calculated from electrical constants[2] for soil is 52 feet for 100 kc. which is within the range of values obtained experimentally.

The large spread observed in the values for k is probably due to the difficulty of carrying out careful experiments in the field. In practical effect, the results range from introducing a 10:1 reduction in signal on round trip to being negligible, when comparing transmission through air and soil.

2 See Report for Phase I p. 33.

PROGRAM FOR THE NEXT INTERVAL

I. Work will continue on improving the coils.

II. The crossed-coil system will be improved mechanically to reduce the residual voltage due to coupling.

III. Work will continue on the pulsed system in improving the gate circuits employed to increase signal to noise ratio.

IV. Work on the grid-dip oscillator system will continue as soon as the necessary approval is obtained.

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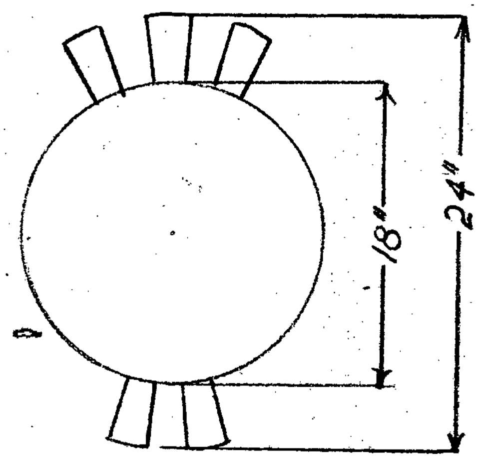
APPENDIX A

Description of Coil



Each coil contained 110 turns of 52 strands of #38 enameled copper wire, wound spider-web fashion on masonite forms. The dimensions of the form are shown in the figure. There were 19 pegs and 19 spaces. The coils had an inductance of 10.3 mh with a distributed capacity of 38.6 mmf. The Q at the operating frequency of 90 kc. was 130.